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Reliability of offshore wind power production under extreme wind conditions. Deliverable D 9.5. Work Package 9: Electrical grid

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Reliability of offshore wind power production under extreme wind conditions

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Abstract:

Reliability of offshore wind production under extreme wind conditions was investigated in this report. The wind power variability from existing and future large offshore wind farms in Western Denmark were simulated using the Correlated Wind model developed at Risø. The analysis was done for five years, with each year simulated with five random seeds, leading to a total of 25 annual wind power time series for six large offshore wind farms, summing up to a little over 330 wind turbines. Two storm control strategies were used. The analysis involved several aspects inspired from reliability studies. The aspects investigated are storm events occurrences and durations, storm control strategy impact on the capacity factor (lost production), the loss of production (power produced from wind drops below a certain threshold due to high wind speeds and storm controller) and finally, the wind power production ramp rates and reserves requirements.

Contents

STATUS, CONFIDENTIALITY AND ACCESSIBILITY										
Status				**Confidentiality**				**Accessibility**	
S0	Approved/Released			**R0**	General public	**(X)**		Private web site	
S1	Reviewed			**R1**	Restricted to project members			Public web site	**(X)**
S2	Pending for review			**R2**	Restricted to European. Commission			Paper copy	
S3	Draft for comments	**X**		**R3**	Restricted to WP members + PL				
S4	Under preparation			**R4**	Restricted to Task members +WPL+PL				

PL: *Project leader* **WPL:** *Work package leader* **TL:** *Task leader*

1. Introduction

In order to meet the very ambitious plans of developing clean and sustainable energy, like the 20% renewable in EU by 2020 [1], some countries plan to install significant capacity of offshore wind farms. Denmark, for example, plans for 50% wind in 2025 [2] and the vast majority of the new installations will be large offshore wind farms. Offshore wind farms are more exposed to extreme wind conditions, as weather phenomena are more extreme at sea.

This makes the subject of offshore wind power production reliability an increasingly important research subject. There are several factors the reliability of wind farms depends on: wind turbines, the internal power collection grid of the wind farm, the grid connection, the power transmission grid, etc. However, critical situations are when the whole wind farm trips [3]. One reason for a wind farm tripping is extreme wind conditions.

This report presents the results of investigating the reliability of offshore wind farm production under extreme wind conditions. The analysis is done at wind farm level and at power system area level. At the wind farm level, the analysis aims at quantifying the impact that storm control strategies have on the availability of the wind farm during storms. At power system area level, on top of the storm control strategy, the spatial distribution of the offshore wind farms is investigated. For that, two scenarios are considered.

The simulations are done using the Correlated Wind (CorWind) simulation software. It simulates wind power variability for a large number of wind turbines over large areas.

Section 2 presents the software used to simulate the wind power variability from the large offshore wind farms in Western Denmark. The two storm control strategies used in the simulations are presented in Section 3, while the scenarios considered are given in Section 4. The simulation and analysis results of offshore wind power reliability are presented in Section 5. Before the concluding remarks that end the report, a small discussion related to the results and future work is presented.

2. CorWind simulation software

The analyses presented in this report are based on simulations with the CorWind power time series simulation model, developed at Risø DTU [4]. CorWind can simulate wind power time series over a large area such as a power system region and in time scales where the wind turbines can be represented by simple steady state power curves, i.e. typically greater than a few seconds. CorWind can be used e.g. for comparison of the impact of the site selection of future wind farms on the system reserves requirements.

CorWind is an extension of the linear and purely stochastic PARKSIMU model [5] - [7], which simulates stochastic wind speed time series for individual wind turbines in a wind farm, with fluctuations of each time series according to specified power spectral densities and with correlations between the different wind turbine time series according to specified coherence functions. The coherence functions depend on frequency and space, ensuring that the correlation between two wind speed time series will decrease with increasing distance between the points. Moreover, the slow wind speed fluctuations are more correlated than the fast fluctuations. Finally, the stochastic PARKSIMU model includes the phase shift between correlated waves in downstream points, ensuring that correlated wind speed variations will be delayed in time as they travel through the wind farm. These model properties ensure that the summed power from multiple wind turbines will have realistic fluctuations, which has been validated using measured time series of simultaneous wind speeds and power from individual wind turbines in two large wind farms in Denmark [8].

The CorWind extension of PARKSIMU is intended to allow simulations over a large areas and long time periods. The linear approach applied in PARKSIMU assumes constant mean wind speeds and constant mean wind directions during a simulation period, which limits the geographical area as well as the simulation period significantly – typically to the area of a single wind farm and to max 2 hours periods. CorWind uses reanalysis data from a climate model to provide the mean wind flow over a large region, and then adds a stochastic contribution using an adapted version of the PARKSIMU approach that allows the mean flow to vary in time and space.

For the present studies, the climate model data is provided by the Regional Model (REMO), developed at Max-Plank Institute (MPI) [9]. A set of data covering historical data for all Europe in 25 years, i.e. 1979 – 2003 with a resolution of 50km × 50km in space and 1 hour in time is available. Figure 1 shows the resolution of the applied REMO data for Denmark.

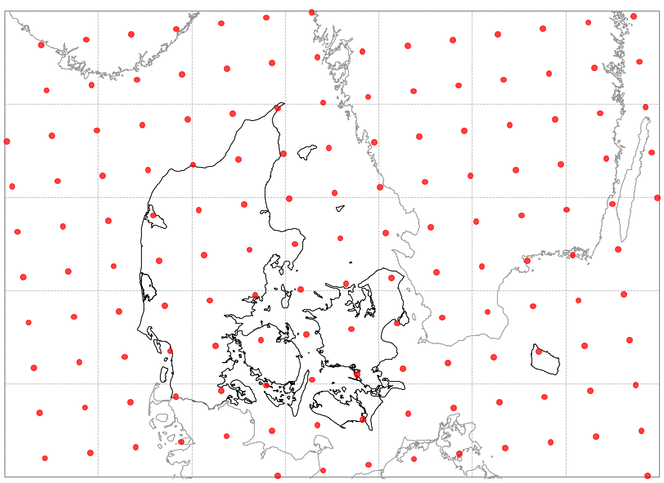


Figure 1 Resolution of applied climate model data provided by Max Plank Institute in Germany

For each of the 50km × 50km points of the REMO model, the given wind speed represents an average over the area. Moreover, the REMO data refers to 10 m height above ground. For a specific wind turbine micro site, it is therefore necessary to scale the REMO wind speed to obtain the hub height wind speed at the specific site. For the present studies, a simple scaling by a constant is applied, and this constant is calibrated so that the specified annual mean wind speed at the specific wind turbine is obtained. This is a very simple approach, which can be questioned, especially when the focus is on the storm wind speeds with relatively low probability. The impact of this simplified scaling will be discussed further in chapter 5 in relation to the credibility of the calculated reliability indices.

A result of a CorWind simulation is shown in Figure 2. The climate model provides the mean flow (CMdata), which is seen to be very smooth. The modified PARKSIMU model is then applied to simulate the fluctuations that are not included in the CMdata. This is done for the individual wind turbine, where the resulting simulation for a single wind turbine (A1) is also shown in the figure. Finally, the average of wind speed from all wind turbines in the wind farm is shown. The present reliability study is based on the wind farm average wind speeds and on total wind farm power, which are calculated as the sum of power from individual wind turbines.

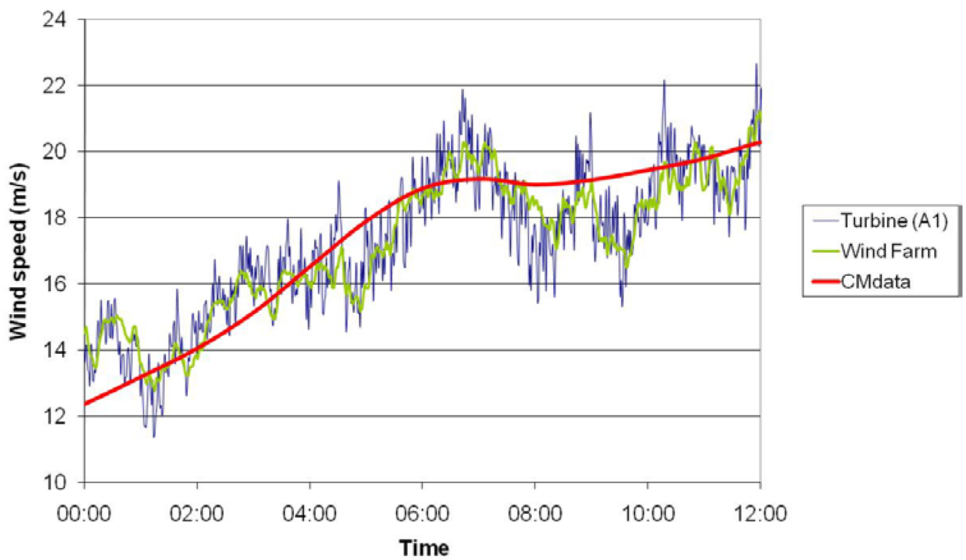


Figure 2 Comparison of variability of a single wind turbine wind speed, the average wind speed in the wind farm, and the climate model input mean value

3. Storm control of wind turbines

The typical power curve of a modern wind turbine is presented in Figure 3. The wind turbine will shut down when the average wind speed reaches a certain value denoted V_4 in the figure. The typical shutdown wind speed is 25 m/s. When the average wind speed drops below the shutdown value, the wind turbine starts again. To prevent frequent restarts and shutdowns, hysteresis is often applied, so that the wind turbine starts up only when the average wind speed reaches a value V_3 lower than the shutdown wind speed.

There are other ways of dealing with the wind turbine operation during very high wind speeds, like the so-called Enercon Storm Control System [10]. This control strategy prevents sudden shut downs of the wind turbine. This is done using a modified power curve, shown in Figure 4. In this case, the wind turbine does not automatically shuts down at a certain wind speed but it starts reducing the power at a wind speed, V_{storm} in Figure 4, smaller than the shut down wind speed. If the wind speed increases further, the wind turbine keeps reducing the power until it reaches zero and thus stops. The wind speed at which the wind turbine would be fully stopped is higher than the typical shut down wind speed (25 m/s). Using this storm control strategy, the wind turbine avoids sudden shot downs and start ups at high wind speeds.

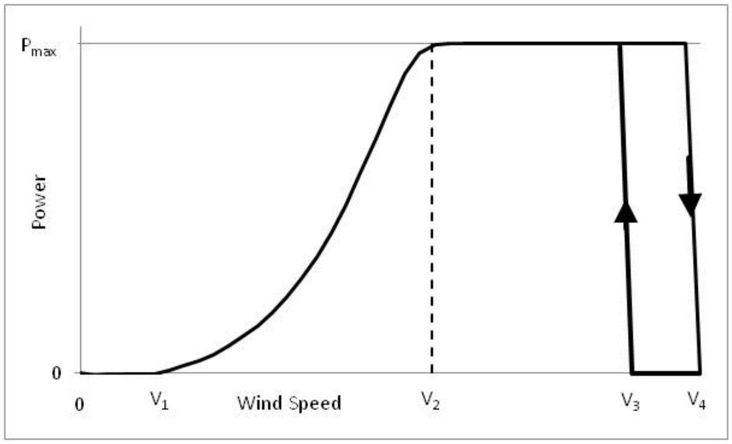


Figure 3 Typical wind turbine power curve

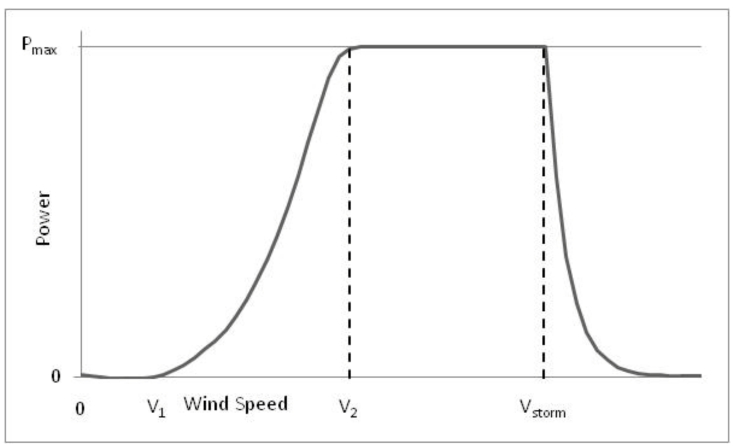


Figure 4 Enercon-type power curve

In this work, storm control strategies similar to the ones presented above were used. However, the present version of CorWind assumes a unique power curve, and therefore hystereses were not included. Thus, the control strategy that shuts down the wind turbine when the 1-min average wind speed reaches 25 m/s starts-up again when the same average wind speed gets lower than 25 m/s. This strategy is similar to the one shown in Figure 3 with $V_4 = V_3 = 25$ m/s. This strategy will be further addressed to as “Hard Storm Transition” (HST) control. The second storm control strategy, inspired from the Enercon storm control, implies that the produced power decreases when the 1-min average wind speed exceeds 20 m/s and stops completely when 30 m/s are reached. This control strategy will be further addressed as “Soft Storm Transition” (SST) control. The power curves associated with those storm control strategies are presented in Figure 5.

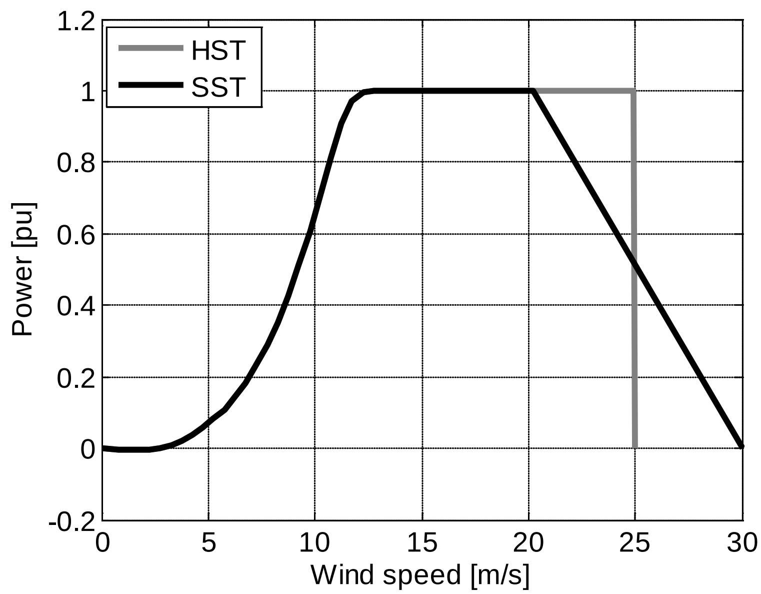


Figure 5 Power curves used in the simulations

4. Simulation case

Future wind farms installed in Denmark will be dominantly off shore. Several possible locations have been identified by the Danish Energy Authority [11]. In order to assess the impact of the geographical spreading of the wind farms over the power systems reserve requirements, a simulation case has been specified.

The six wind farms that are simulated are shown in Figure 6. The first wind farm is the existing wind farm in Horns Rev. The second wind farm is the Horns Rev 2, which is expected to be commissioned by the end of 2009. The last 4 wind farms are among the positions in [11].

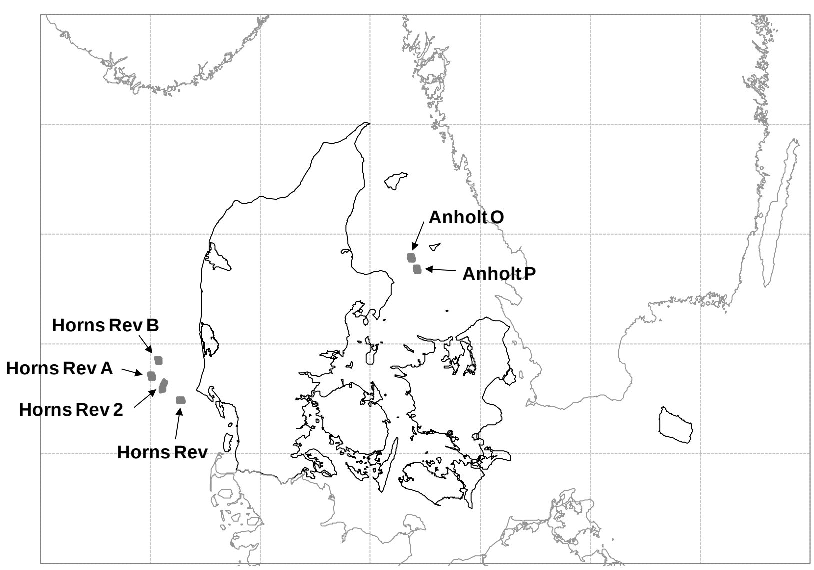


Figure 6 Simulated wind farms

Data for Horns Rev and for Horns Rev 2 is given in details, including the sizes and positions of the individual wind turbines. The wind turbine size and relative positions have some influence on the simulation result, but the main most important parameter is the total power and the geographical position of the wind farm (Figure 6). Another assumption is the annual mean wind speed, which is applied to calibrate the MPI weather model date. These mean wind speeds are estimates based on the report on future Danish offshore sites [11]

The main wind farm data applied in the simulation is summarised in **Table 1**. Actual position and wind turbine ratings are used for the two existing Horns Rev wind farms, while it is assumed that each new wind farms consists of 40 × 5.0 MW wind turbines arranged in an array with 8 rotor diameters between rows and 6 rotor diameters between the turbines in each row.

Table 1. Data for the 6 simulated wind farms

Name	Symbol	Wind turbine power	Total power	Annual mean wind speed
Horns Rev	HR1	80 × 2.0 MW	160 MW	9.6 m/s*)
Horns Rev 2	HR2	91 × 2.3 MW	209 MW	10.4 m/s*)
Horns Rev A	HRA	40 × 5.0 MW	200 MW	10.6 m/s*)
Horns Rev B	HRB	40 × 5.0 MW	200 MW	10.5 m/s*)
Anholt O	DAO	40 × 5.0 MW	200 MW	9.0 m/s*)
Anholt P	DAP	40 × 5.0 MW	200 MW	9.0 m/s*)

*)the annual mean wind speeds are estimates based on [11].

All wind farms are simulated for 5 years of Reanalysis data, 1999 – 2003. The time step of the simulation is selected to 1 minute. The stochastic part is simulated with a period time of 1 day. This is a compromise between computer simulation time and simulation accuracy. Longer period times are possible, but it would require longer computer simulation time, and yet not add variability because the stochastic part includes variability faster than one day. To ensure that the stochastic randomness is still properly represented, each year was simulated with 5 different random seeds for the stochastic part. Thus, a total of 25 years, i.e. 5 years x 5 seeds, of simulation time series are used for the analysis.

The idea is now to analyse the reliability of the individual wind farms during extreme winds events (storms) as well as to compare two scenarios:

- The concentrated scenario: Horns Rev and Horns Rev 2 are supplemented with 2 new wind farms Horns Rev A and Horns Rev B.
- The spread scenario: Horns Rev and Horns Rev 2 are supplemented with 2 new wind farms Anholt O and Anholt P.

The concentrated scenario is clearly beneficial from the point of view of annual energy production, because the annual mean wind speed is significantly higher in the Horns Rev area than in the Anholt area. However, from the point of view of wind power fluctuations, the concentrated scenario will provide faster and larger variations and therefore will probably require larger power reserves, especially during periods with extreme wind speeds.

5. Simulation results

For each simulated year, the saved results consist of one-minute time series of the average wind speed over each wind farm and the total power produced by that wind farm. The analysis was done in terms of wind power production reliability indexes inspired from the standard power system reliability analysis techniques and in terms of operational impact of wind power on the power system.

The attention is focused on the operation of wind farms under extreme wind conditions. Therefore, the first step was to quantify the frequency and duration of periods with extreme wind conditions. For this purpose, Extreme Wind Periods (EWP) where defined as the periods of time starting when the wind speed exceeds 25 m/s and lasting until the wind speed decreases below 20 m/s. This definition is similar to the standard wind turbine storm shut down control with hysteresis as in Figure 3. Since the focus is on large wind farms, the average wind speed over the wind farm is the one that defines the start and stop of the EWP. By this definition, the EWP are solely defined by the wind speed and therefore independent of the storm control strategy used.

When the aim is to quantify the impact of the extreme winds on the power produced by the wind farms, the focus is on the down ramping. For this purpose, the periods where the down ramping of power is caused by storm control are first identified, so that down ramping due to storms can be distinguished from down ramping due to decrease in wind speeds at lower wind speeds. These periods are called the Storm Control Event (SCE) periods. Since SST control is becoming active at 20 m/s and HST at 25 m/s, SCE period is considered to start when the average wind farm wind speed crosses 20 m/s. In order to maintain some hysteresis, an SCE period then stops when the wind speed gets lower than 15 m/s, which is in due time before the power starts ramping down due to decreased wind speeds. Obviously this SCE definition leads to having a higher number and longer duration of SCEs than EWPs. However, the idea with the SCE periods is to quantify the power ramping in those periods, and not to quantify the frequency and duration of the SCE periods.

At power system area level, the results are analyzed and compared for two scenarios, presented in §4. In this case, EWP starts when all the wind speeds (four wind farms in each scenario) cross 25 m/s and it stops when all of them are getting lower than 20 m/s. Basically, it is a “all on – all off” strategy. SCE for power system area level is similarly defined, with 20 and 15 m/s the border values.

5.1. Frequency and duration of occurrences

This section analyses the frequency and duration (F&D) of EWP’s as reliability index to quantify the impact of storms on the power system reliability of wind farms. This approach is equivalent to reliability assessment of failures of other power system components including power plants as e.g. applied by Negra [12]. The frequencies and durations of EWP's are calculated for both individual wind farms and for power system area level.

The individual wind farm number of occurrences, for each year and each seed, are shown in Figure 7. The number of occurrence is influenced by both the year, thus the REMO data, and by the seed, thus the higher (> 1 per day) frequencies.

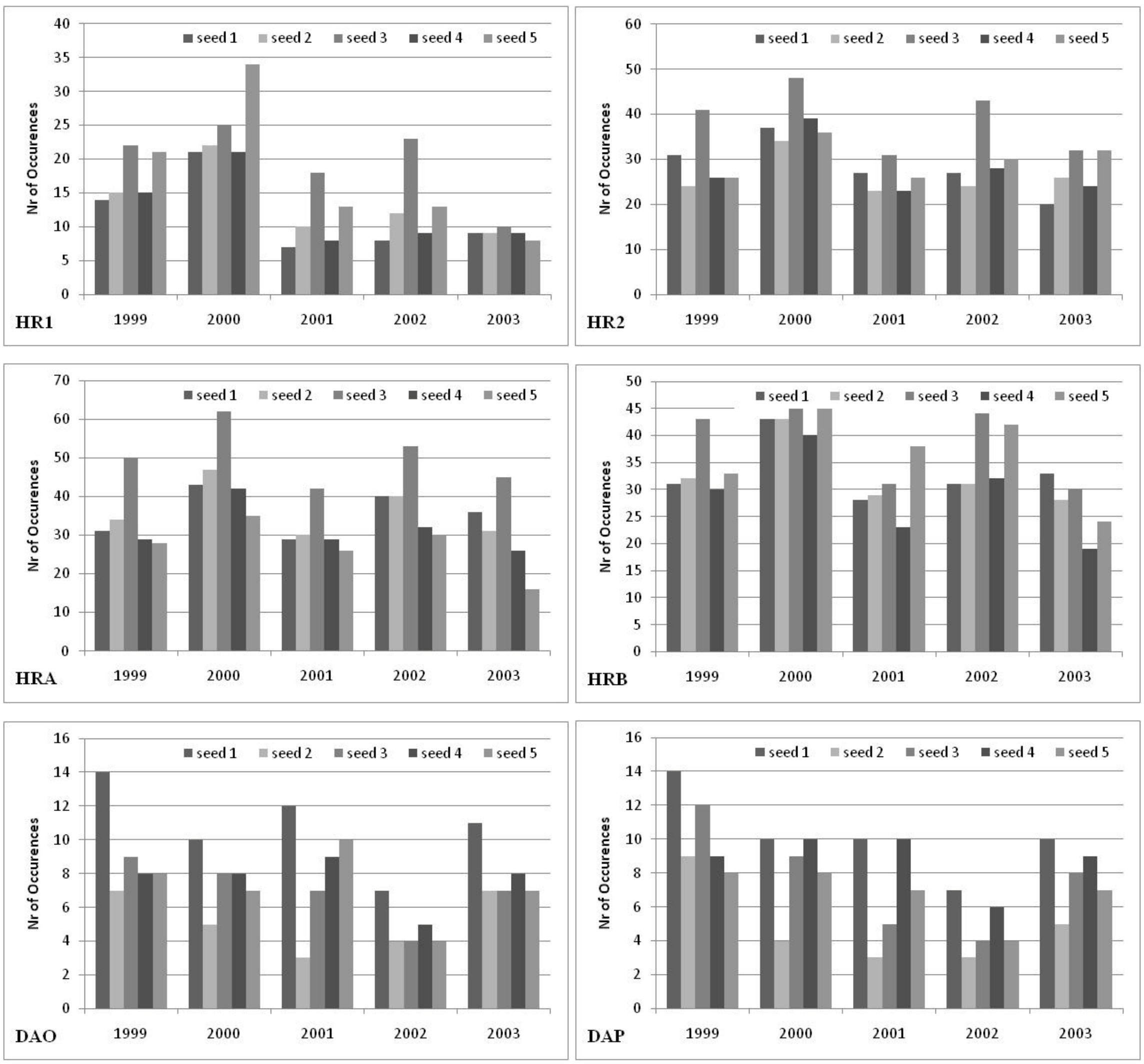


Figure 7 Number of occurrences; individual wind farms

The following observations are immediately made from Figure 7:

The numbers of occurrences in the simulations are generally higher than expected, although no analysis of measured data has confirmed this. The number of occurrences in the simulations is very dependent on the up-scaling of the REMO data given at 10 m height to wind turbines hub heights, which is presently done by a constant scaling factor as explained in chapter 2. To improve this and to ensure sufficient confidence in the results, it will be necessary to analyse the distribution of wind speeds at the offshore locations. Unfortunately, the UPWIND budget does not give room for such an analysis. Analysis of measured data at Horns Rev will be done in a national research project, where the measured wind speeds will also be compared to the simulated wind speeds.

The different locations with different annual mean wind speeds have a significant influence on the number of occurrences in the simulations. HRA and HRB with the highest mean wind speeds out in the open North Sea have the highest number of occurrences, while DAO and DAP with the lowest mean wind speed in the inner sea of Kattegat have the lowest number of occurrences. In between is HR1 and HR2, with HR1 as the wind farm at Horns Rev with least number of occurrences and the smallest annual mean wind speed.

The historical year has some influence on the result. This is especially clear for year 2000 at the Horns Rev wind farms in the North Sea, where the numbers of occurrences are high due to a year with several storms. Apparently the storms in 2000 were not strong enough to influence significantly the number of occurrences on DAO and DAP in the inner sea.

The influence of the lower frequencies (REMO data) and the higher frequencies (stochastic part of the model) can be seen in Table 2, where minimum, maximum and the ratio between them, for each simulated wind farm and year, are presented. The average ratio between minimum and maximum number of occurrences, for all wind farms and for all years, is 0.56. The minimum ratio is 0.25 – meaning that the random selection of the seed can lead to four times more occurrences, while the maximum ratio of 0.85 indicate that, on the other hand, there are years and seeds for which the variation is small.

Table 2 Number of occurrences; min, max and ratio

WF		1999	2000	2001	2002	2003
HR1	min	14	21	7	8	8
	max	22	34	18	23	10
	min/max	**0,64**	**0,62**	**0,39**	**0,35**	**0,80**
HR2	min	24	34	23	24	20
	max	41	48	31	43	32
	min/max	**0,59**	**0,71**	**0,74**	**0,56**	**0,63**
HRA	min	28	35	26	30	16
	max	50	62	42	53	45
	min/max	**0,56**	**0,56**	**0,62**	**0,57**	**0,36**
HRB	min	30	40	23	31	19
	max	43	47	38	44	33
	min/max	**0,70**	**0,85**	**0,61**	**0,70**	**0,58**
DAO	min	7	5	3	4	7
	max	14	10	12	7	11
	min/max	**0,50**	**0,50**	**0,25**	**0,57**	**0,64**
DAP	min	8	4	3	3	5
	max	14	10	10	7	10
	min/max	**0,57**	**0,40**	**0,30**	**0,43**	**0,50**

On the other hand, when we look at the total storm duration, the random seed seems to have smaller influence. In Table 3, the total duration, in hours, of the storm events for HR1 wind farm is given. The data are given for each simulated year and seed. The difference between the random seeds, for the same year, is not significant. If we normalize the values with, e.g. seed 1 considered as the base case, the total duration of the storm events are similar for all seeds, with just a handful of cases when the difference is larger, e.g. for 2002 – seed 3. This is shown in Table 4. The results are similar for the rest of the simulated wind farms.

Table 3 Total **s**torm duration in hours for HR1

	seed 1	seed 2	seed 3	seed 4	seed 5
1999	199	190	204	191	204
2000	189	192	194	185	214
2001	89	111	119	105	109
2002	68	79	96	73	70
2003	86	94	92	93	87

Table 4 Total storm duration, normalized values, for HR1

	seed 1	seed 2	seed 3	seed 4	seed 5
1999	1	0,95	1,02	0,96	1,02
2000	1	1,02	1,03	0,98	1,14
2001	1	1,25	1,34	1,18	1,23
2002	1	1,17	1,41	1,08	1,03
2003	1	1,09	1,08	1,09	1,01

Thus, one can conclude that while the random seed of the stochastic part of the model influences the number of occurrences significantly, it only marginally influences the total duration of the storm events in a given year.

Table 5 Storm duration statistics

	hours	1999	2000	2001	2002	2003
HR1	min	1,87	1,36	1,58	1,64	2,05
	max	36,70	22,90	39,46	15,71	25,26
	mean	11,72	8,12	10,37	6,55	10,06
	sum	197,54	194,91	106,49	77,16	90,25
HR2	min	1,46	1,26	1,23	1,12	1,88
	max	46,12	27,00	48,62	19,50	32,32
	mean	10,49	9,14	8,93	8,01	7,72
	sum	300,30	351,96	230,87	236,60	200,19
HRA	min	1,36	1,48	1,35	1,07	1,45
	max	45,00	28,49	51,15	21,83	31,02
	mean	9,81	8,84	8,36	8,01	8,12
	sum	324,43	393,41	255,50	301,34	228,06
HRB	min	1,40	1,13	1,20	1,00	1,79
	max	44,25	28,49	51,09	21,50	32,47
	mean	9,09	8,54	8,34	7,52	9,57
	sum	302,76	374,41	242,87	264,70	236,96
DAO	min	1,93	2,83	1,79	2,69	2,22

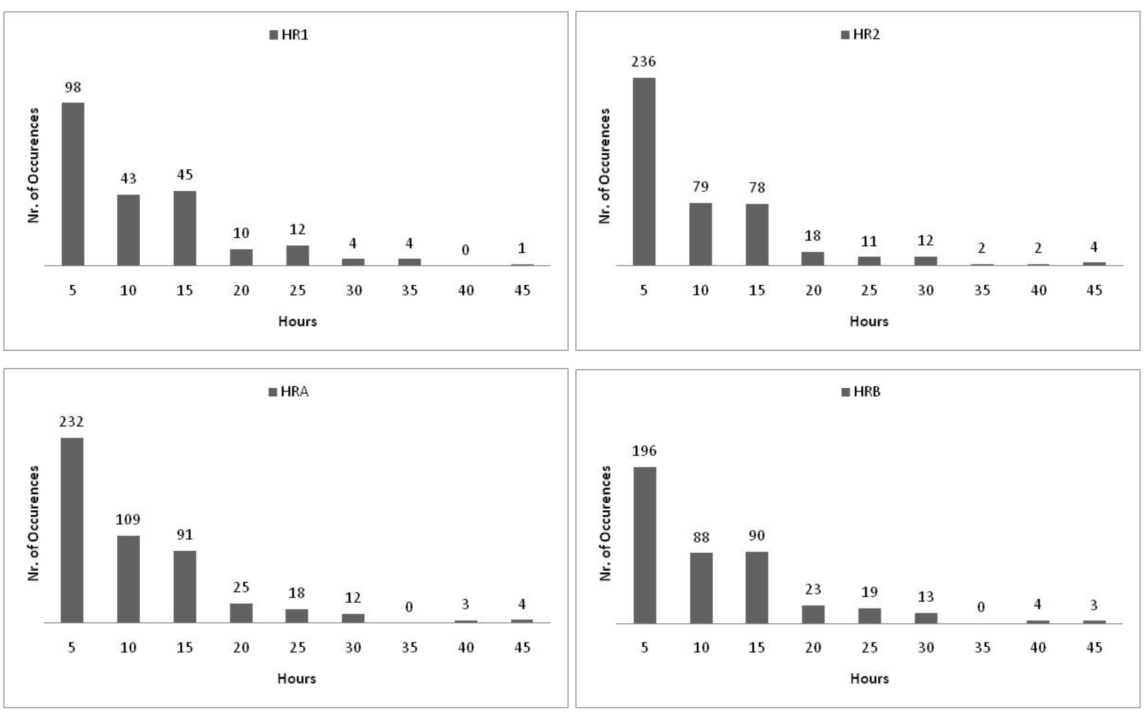
	max	17,24	17,00	11,24	7,41	16,33
	mean	6,11	7,74	4,86	4,66	6,78
	sum	54,75	56,44	35,87	21,81	53,20
DAP	min	1,48	1,98	2,19	2,51	2,30
	max	20,09	17,36	10,13	7,21	13,22
	mean	5,83	7,62	4,77	4,48	6,66
	sum	58,76	57,42	30,58	20,70	49,49

The statistics of the storm events, for each wind farm and simulated year are given in Table 13. The values are the average over the five seeds used in the simulations.

Table 6 Storm events; Average values per wind farm

Wind farms		HR1	HR2	HRA	HRB	DAO	DAP
Storm duration in hours	min	1,70	1,39	1,34	1,30	2,29	2,09
	max	28,01	34,71	35,50	35,56	13,84	13,60
	average	9,37	8,86	8,63	8,61	6,03	5,87
	total/year	133,27	263,98	300,55	284,34	44,41	43,39

Based on the simulations done, the wind farms considered will experience storm events with duration between minimum around 1.3 hours and a maximum of around 36 hours, an average duration of around 7 hours and a total duration over a full year of maximum 300 hours. The detailed values, presented in Table 6, indicate that those values can vary significantly from wind farm to wind farm.



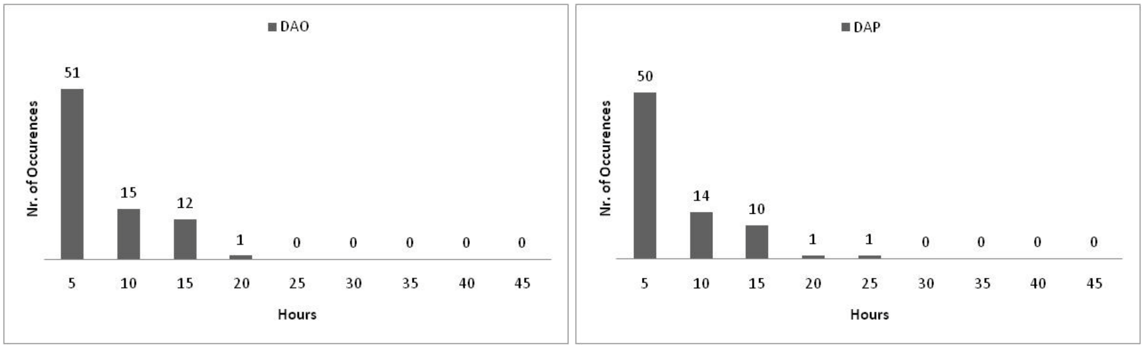


Figure 8 Storm number of occurrences for each wind farm; 5-hours bins

The distribution of the storm occurrences binned by their duration, for each wind farm, is shown in Figure 8. A five hour bin was used, to cover all the storm events. As it can be seen, the vast majority of the events are concentrated in the duration range 1 to 15 hours. In order to see the distribution of the occurrences number in this range, the storm events where binned with 1-hour resolution, see Figure 9.

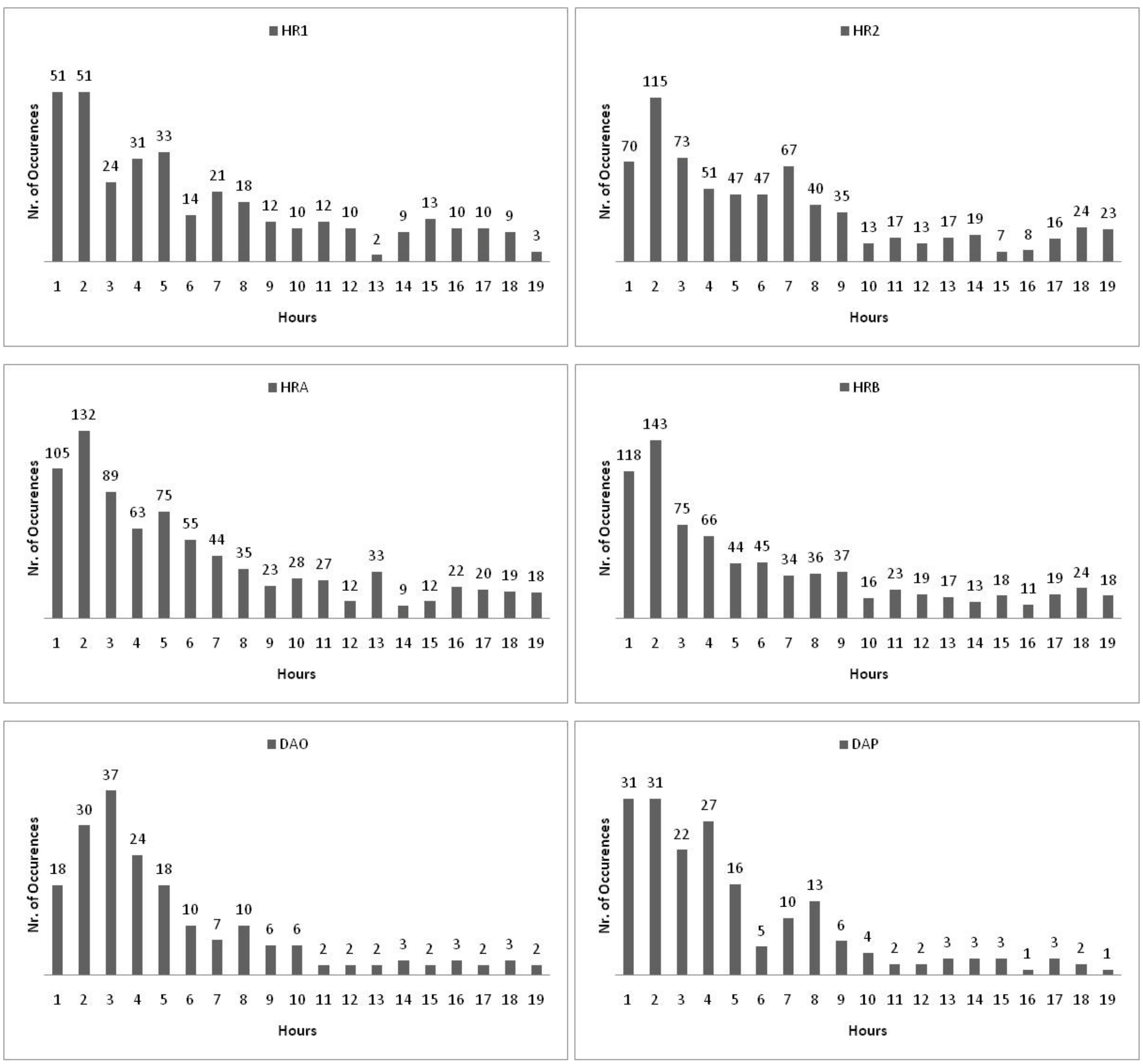


Figure 9 Storm events occurrences for each wind farm; 1-hour bins

The distribution of the 1-hour bin storm occurrences varies from wind farm to wind farm. Storm events with duration between one and two hours are the most common for each wind farm, except for DAO wind farm, for which the most common storm duration seems to be between two and three hours.

At power system region level, a quick way of analyzing the EWPs for each scenario is to simply add the individual wind farm's EWPs. However, this would lead to an exacerbation of the EWPs weight in the operation of the power system because several of them are happening at the same time (some of the wind farms are close to each other). To avoid that, in the case of a power system region, EWPs are defined as the periods of time starting when all the wind farms shutting down because of high wind speeds, i.e. the average wind speed over each of the offshore wind farms considered in each scenario, crosses 25 m/s and ending when all of the wind speed gets lower than 20 m/s. Basically, one can say that this is an "all off – all on" definition of the storm events over a power region.

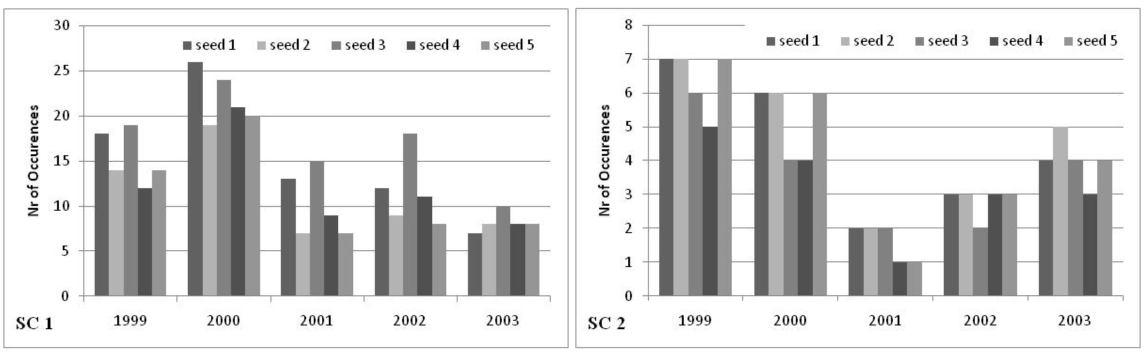


Figure 10 Storm events occurences for each scenario

The resulted storm events occurrences, for each scenario and for each year and seed, are presented in Figure 10.

The seed used in the stochastic part of the model influences the number of occurrences to a smaller extent than in the case of individual wind farms, the ratio between minimum and maximum number of occurrences being slightly higher. For both scenarios the average ratio is app. 0.68, with the second scenario having a variation in the range of 0.58 to 0.79.

Table 7 Number of occurrences; min, max and ratio

		1999	2000	2001	2002	2003
Scenario 1	Min	12	19	7	8	7
	Max	19	28	15	18	10
	Min/Max	0,63	0,68	0,47	0,44	0,70
Scenario 2	Min	5	4	1	2	3
	Max	7	6	2	3	5
	Min/Max	0,71	0,67	0,50	0,67	0,60

On the other hand, the impact of the random seed on the total storm duration seems to be bigger than in the case of individual wind farms. This can be seen in Table 9, where the annual storm durations, given in hours in Table 8, are given normalized with the values for seed 1, for the concentrated scenario. The same values, for the distributed scenario, are given in Table 10 and Table 11. The annual storm duration can be with as much as 40% less for the concentrated scenario and down with more than 70% for the distributed scenario.

Table 8 Total storm duration in hours, scenario 1

	seed 1	seed 2	seed 3	seed 4	seed 5
1999	233	208	228	221	224
2000	294	217	246	246	237
2001	155	120	168	144	124
2002	135	85	141	109	81
2003	101	108	110	110	108

Table 9 Total storm duration, normalized values, scenario 1

	seed 1	seed 2	seed 3	seed 4	seed 5
1999	1	0,89	0,98	0,95	0,96
2000	1	0,74	0,84	0,84	0,81
2001	1	0,77	1,08	0,93	0,80
2002	1	0,62	1,04	0,80	0,60
2003	1	1,08	1,10	1,09	1,07

Table 10 Total storm duration in hours, scenario 2

	seed 1	seed 2	seed 3	seed 4	seed 5
1999	94	77	72	88	112
2000	55	56	47	49	59
2001	73	51	21	22	28
2002	22	22	18	18	23
2003	59	56	58	52	70

Table 11 Total storm duration, normalized values, scenario 2

	seed 1	seed 2	seed 3	seed 4	seed 5
1999	1	0,82	0,76	0,93	1,18
2000	1	1,03	0,86	0,90	1,08
2001	1	0,69	0,29	0,31	0,38
2002	1	0,98	0,82	0,81	1,05
2003	1	0,95	0,97	0,88	1,18

The average values, resulted from the 25 one-year wind speeds time series, for each scenario, are given in Table 12. The results indicate that the total duration of the high wind speed events, over a power system region, can be significantly reduced – more than 60% - by properly selecting the location of the wind farms. Thus, from an average duration of 166 hours of storm events in the first scenario, the mean annual duration is reduced to 52 hours in the distributed scenario.

Table 12 Storm events; Average values per scenario

Scenario		Sc 1	Sc 2
Storm duration in hours	min	81	18
	max	294	36
	average	166	52

The distribution of the storm events occurrences, using a five hours bin, is shown in Figure 11. The differences between the two scenarios are significant, with the second scenario resulting in important reduction of the number of occurrences. The maximum duration of storm is the same for both scenarios, 50 hours.

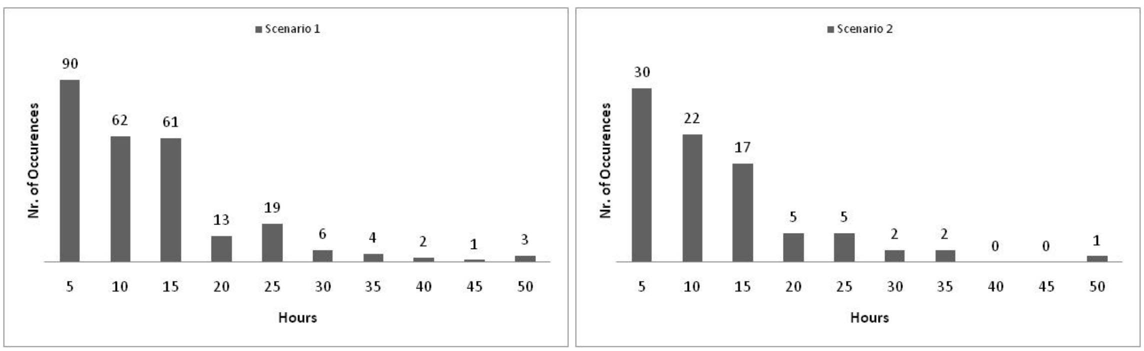


Figure 11 Storm number of occurrences for each scenario; 5-hours bins

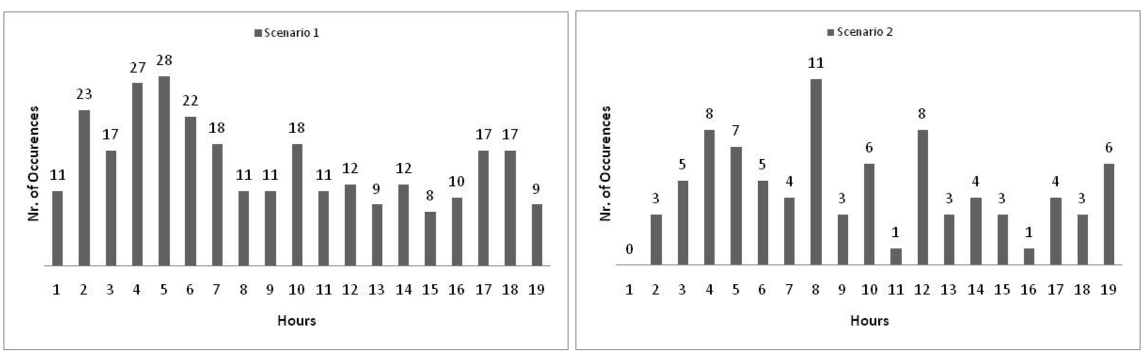


Figure 12 Storm number of occurrences for each scenario; 1-hour bins

The one hour bin distribution, presented in Figure 12, indicates that the two scenarios lead to similar results regarding the duration of the storm.

5.2. Lost energy

This index shows how much production is lost, annually, due to storm events. Depending on the storm control used, the wind turbines will either produce at rated value and then shut down (zero production) or progressively produce less (ramping down) as the wind speed increases. The lost energy is expressed in terms of capacity factor (C_F). The capacity factor is defined as the ratio between the energy produced by the wind turbine and the maximum power that the wind turbine could produce, over a period of time:

$$C_{\mathrm{F}} = \frac{E_a}{N_h \cdot Cap} \tag{1}$$

where N_{h} is the period of time, in hours; typically one year is used; *Cap* is the installed capacity and E_{a} is the energy produced by the wind farm.

Since the same wind speed time series were used in both simulations, the difference in the capacity factor of the individual wind farms will only depend on the storm control strategy used.

In Figure 13 the capacity factor for all the considered wind farms, in the order they are presented in **Table 1**, is shown for all simulated years.

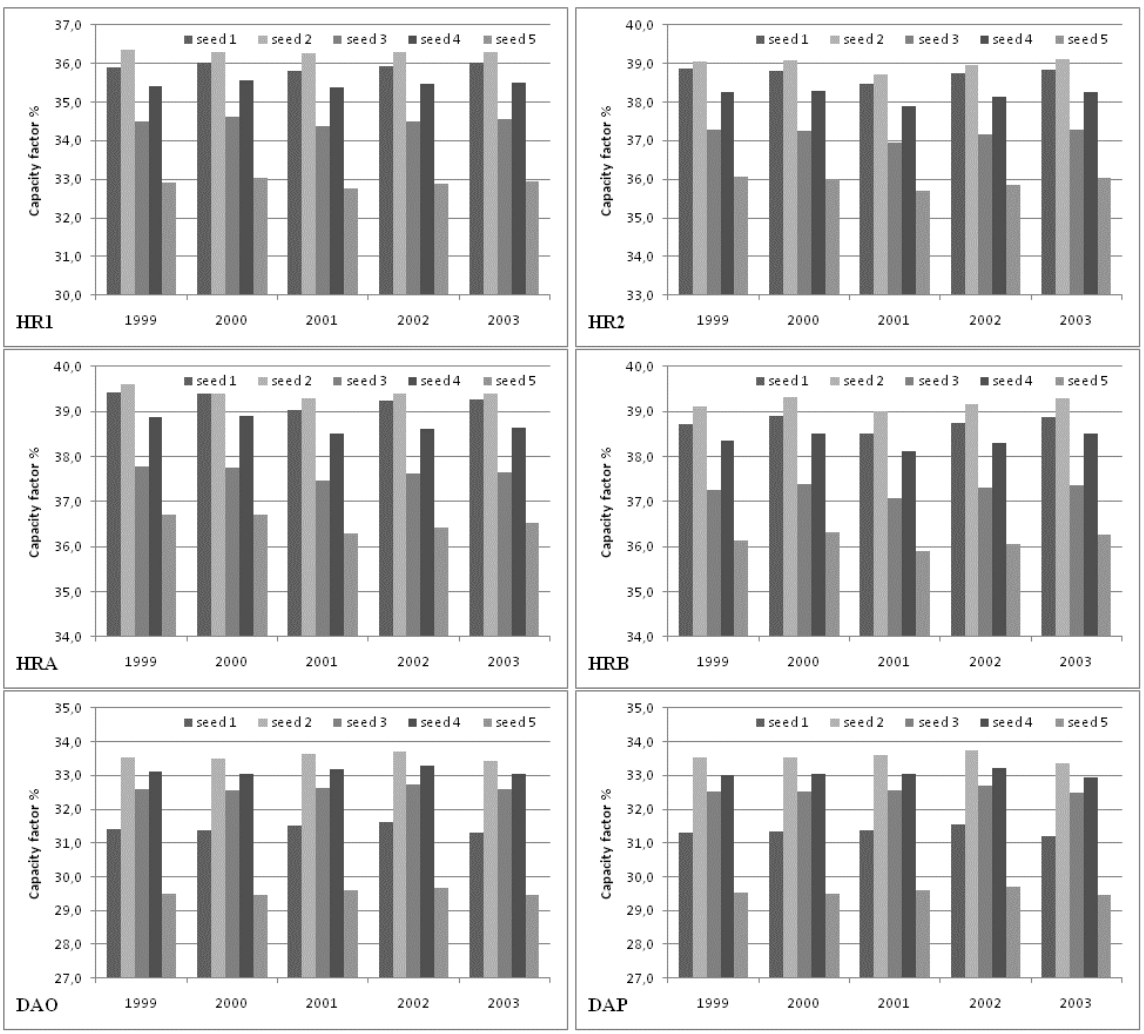


Figure 13 Capacity factor for all the wind farms, HST storm control strategy

The capacity factor is mostly influenced by the low frequency wind speed variations, in our case the ones given by the Reanalysis data. The high frequency variations, determined by the different seed, do not seem to influence a lot, as it can be seen in Figure 13.

The storm control strategy used in the simulations that result in the capacity factors presented in Figure 13 is HST. When using the SST storm control strategy, the capacity factors are slightly lower, as shown in Figure 14.

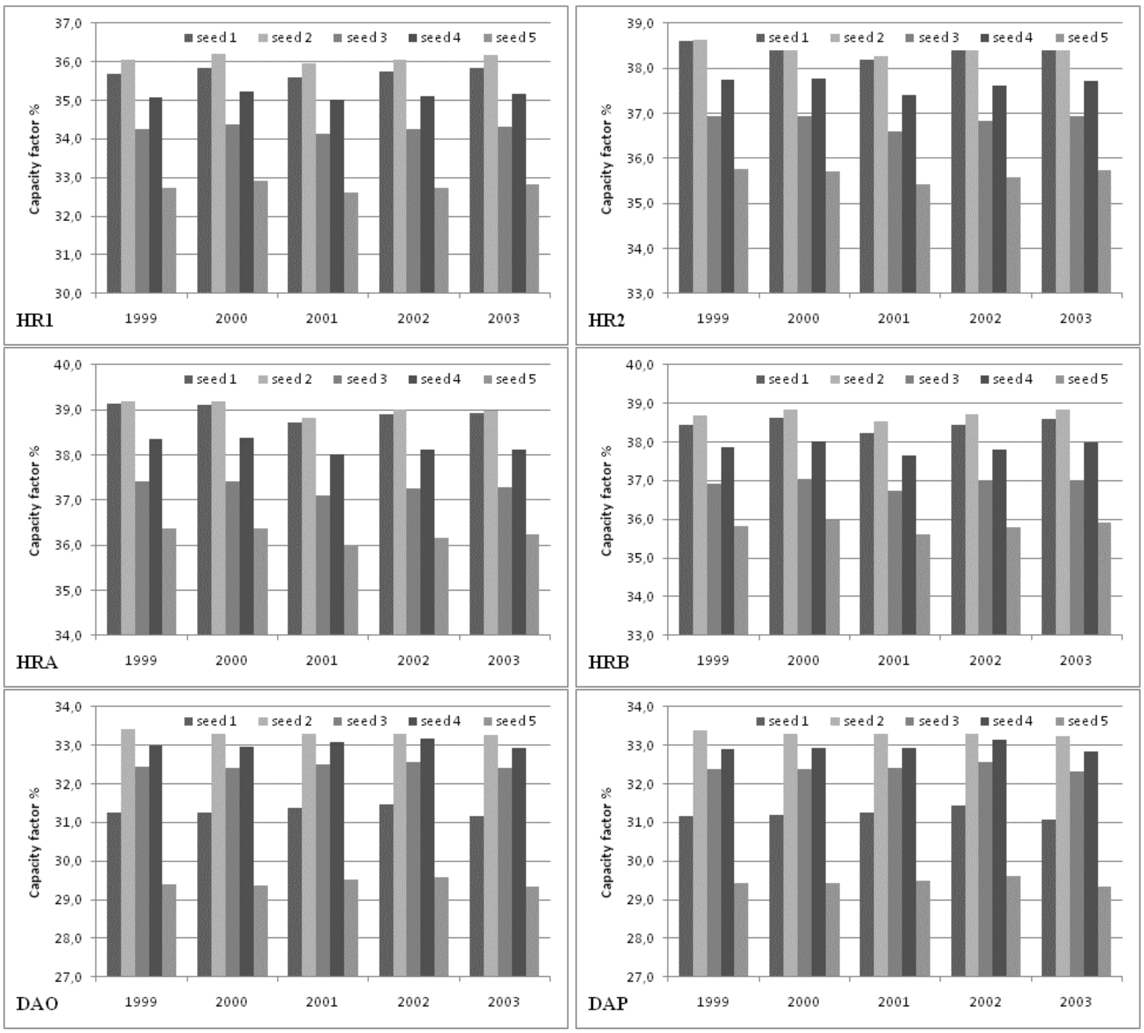


Figure 14 Capacity factor for all the wind farms, “Ramping down” storm control strategy

The difference in the capacity factor for the two control strategies is given in Figure 15. The difference was calculated as HST capacity factor minus SST capacity factor, for each wind farm and for each simulated year.

The impact of the storm control strategy on the wind farm capacity factor is given in Table 13. The average annual lost production differs for the considered wind farms. The storm control strategy can lead to a lost production equivalent with 10 to 35 full load hours.

Table 13 Average lost production for each wind farm

Name	HR1	HR2	HRA	HRB	DAO	DAP
Capacity factor difference %	0,25	0,37	0,39	0,38	0,13	0,12
Equivalent full load hours	21,65	32,80	34,26	33,04	11,02	10,81

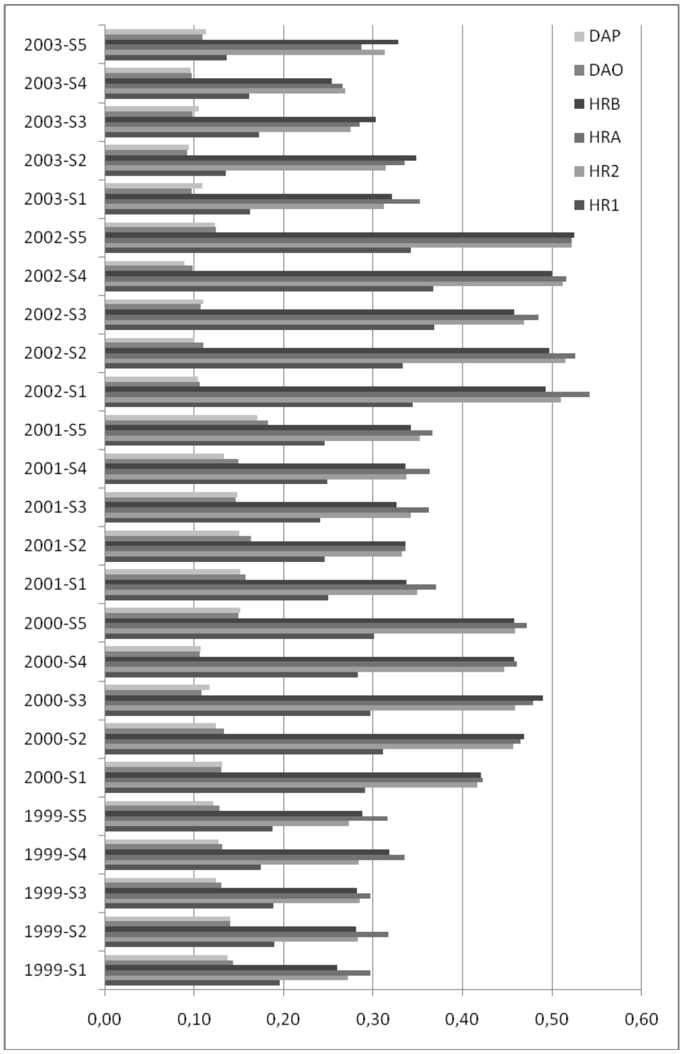


Figure 15 Capacity factor difference; HST - SST

5.3. Loss of production

This index quantifies the periods of time when the wind power production drops below a threshold, for example less than 20% of the installed capacity, due to extreme winds. Such an index is useful for showing how often or for how long individual or a portfolio of wind farms can be expected to produce significantly less than possible due to extreme events like storms. The loss of production is assessed only during SCEs because the periods when the production is low due to low wind speeds is not of interest in this work.

The loss of production is quantified both in hours and as a percent of the total SCE duration.

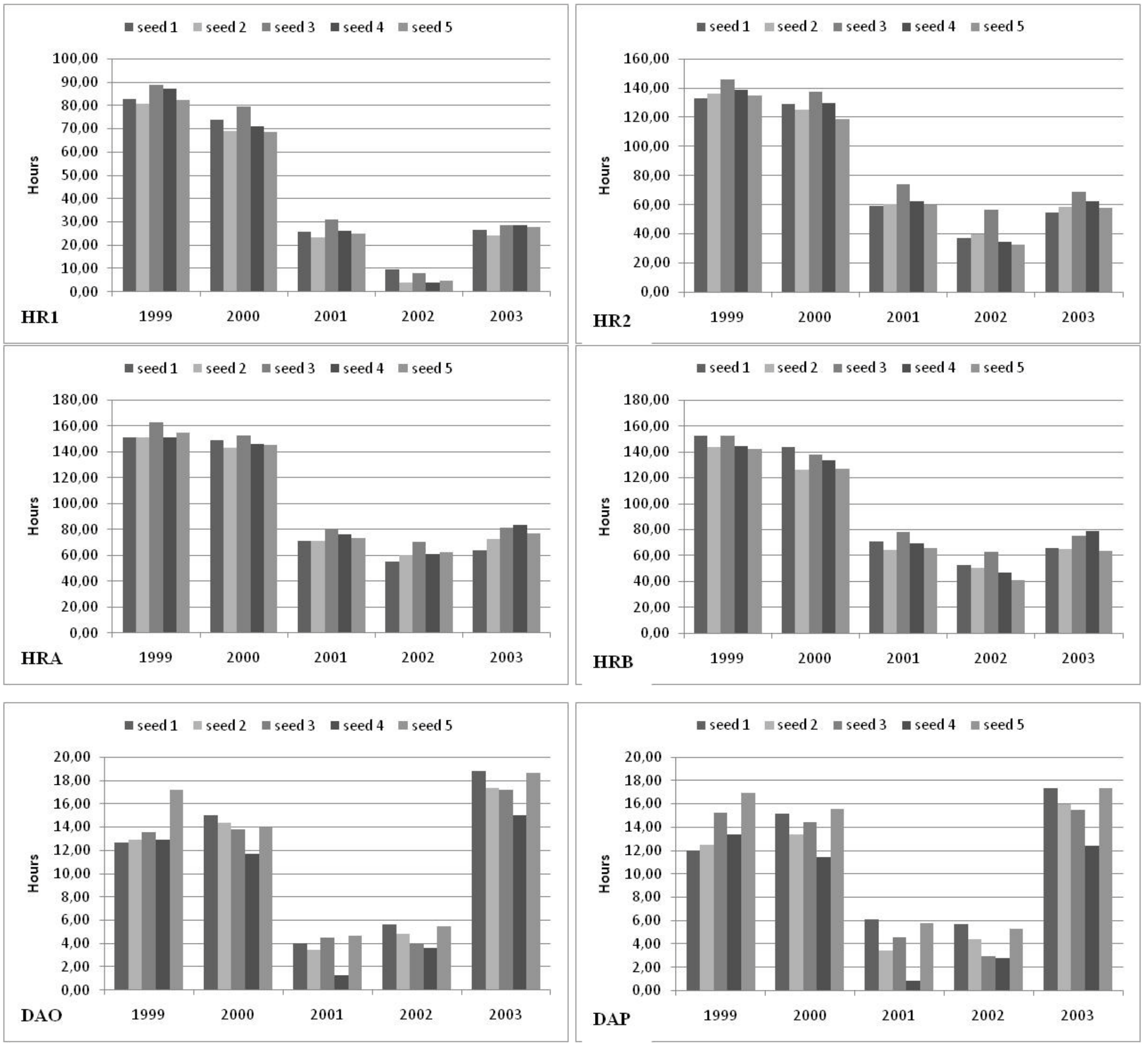


Figure 16 Loss of production hours for each wind farm; HST control

Figure 16 and Figure 17 present the loss of production, in hours and as percentage of total storm duration, respectively, for HST control. Figure 18 and Figure 19 present the loss of production, again in hours and percentage, for SST control. The random seed does not have a significant impact on the results.

The storm control strategy, on the other hand, has a great influence on total duration of the loss of production, with the SST control strategy resulting in less than half total hours of loss of production compared to the HST control strategy.

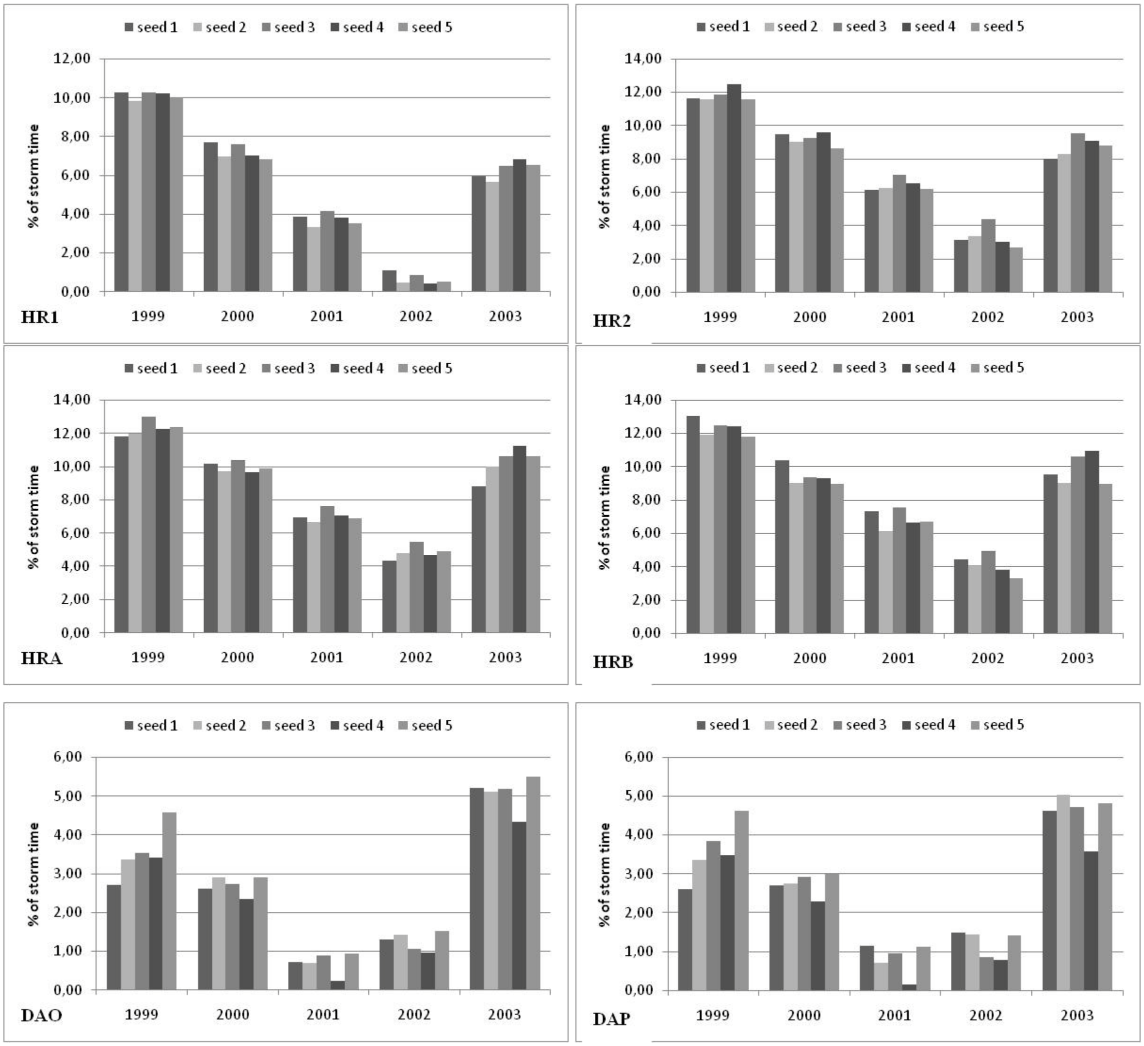


Figure 17 Loss of production as a percentage of total storm duration; HST control

Similar conclusions can be drawn when analysing loss of production as a percentage of the total storm time, for each wind farm and each simulated year, as presented in Figure 18 and Figure 19. When on-off storm control strategy is used, there is loss of production for maximum 10-12% of the total storm time. When ramping down storm control is used, the value drops to half, with an maximum around 5-6%.

The average values, for each wind farm, are presented in Table 14. Those values show that the total hours of loss of production differs significantly from one wind farm to another, going from a maximum of 63 hours for HRA to a minimum of 7,7 hours for DAP.

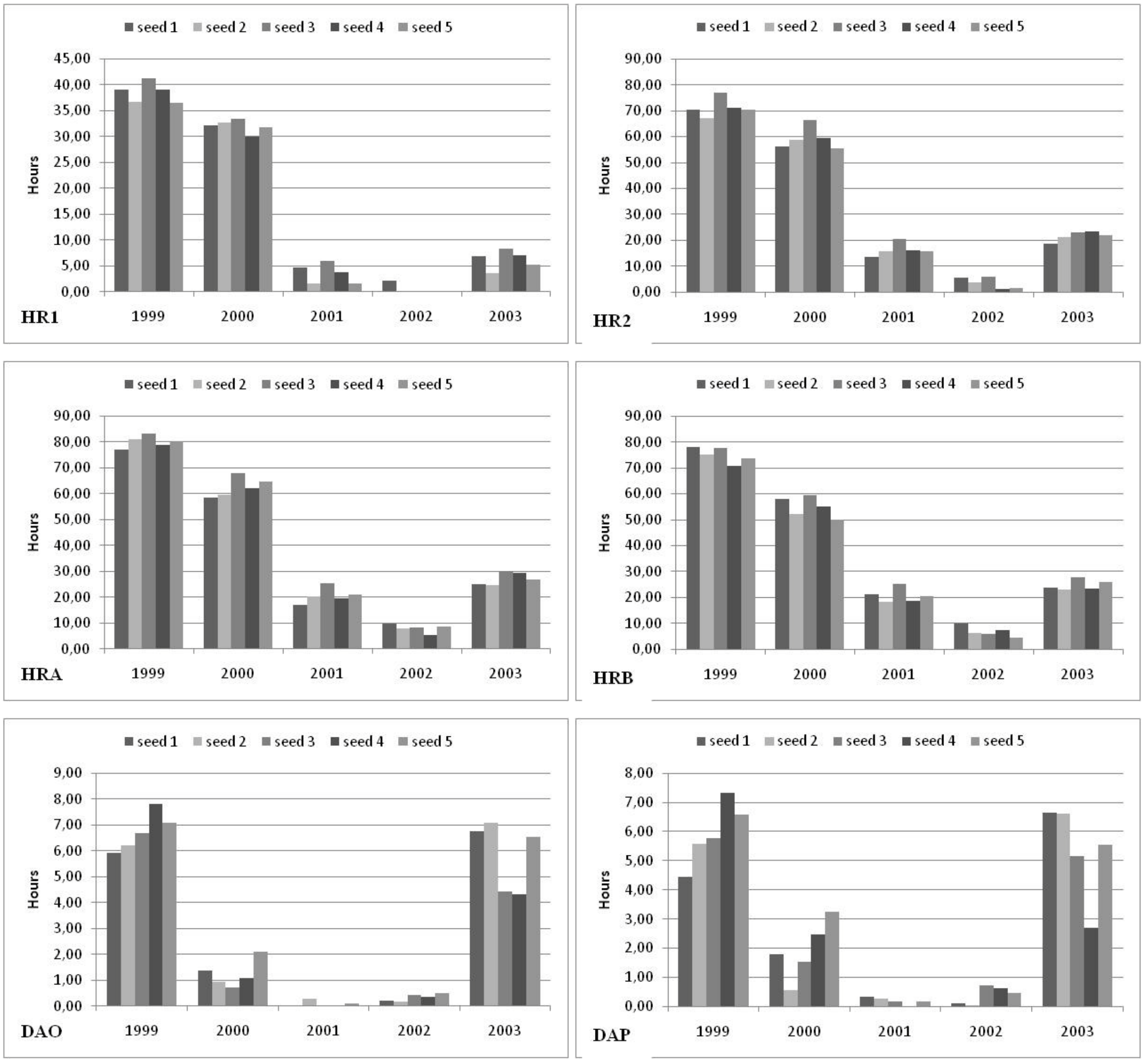


Figure 18 Loss of production hours for each wind farm; SST control

Table 14 Loss of production per wind farm; mean values

Wind farms		HR1	HR2	HRA	HRB	DAO	DAP
Hours	HST	43,2	85,9	102,7	94,2	10,7	10,4
	SST	16,2	34,4	39,7	36,5	2,8	2,8
	Difference	**27,1**	**51,4**	**63,0**	**57,7**	**7,8**	**7,7**
% of storm time	HST	5,6	7,9	8,9	8,5	2,6	2,6
	SST	2,0	3,1	3,4	3,3	0,8	0,7
	Difference	**3,7**	**4,8**	**5,5**	**5,3**	**1,9**	**1,9**

For the power system region, the analysis was done for the two scenarios presented in §4. In this case, the threshold is calculated as to the total installed capacity, i.e. for scenario 1 is HR1+HR2+HRA+HRB. This means that if one or more wind farms are producing less than 20% of their installed capacity, if the total production is not less than 20% of the total installed capacity, then this is not considered a loss of production. Similar to the individual wind farm analysis, the loss of production is calculated only during the storm events.

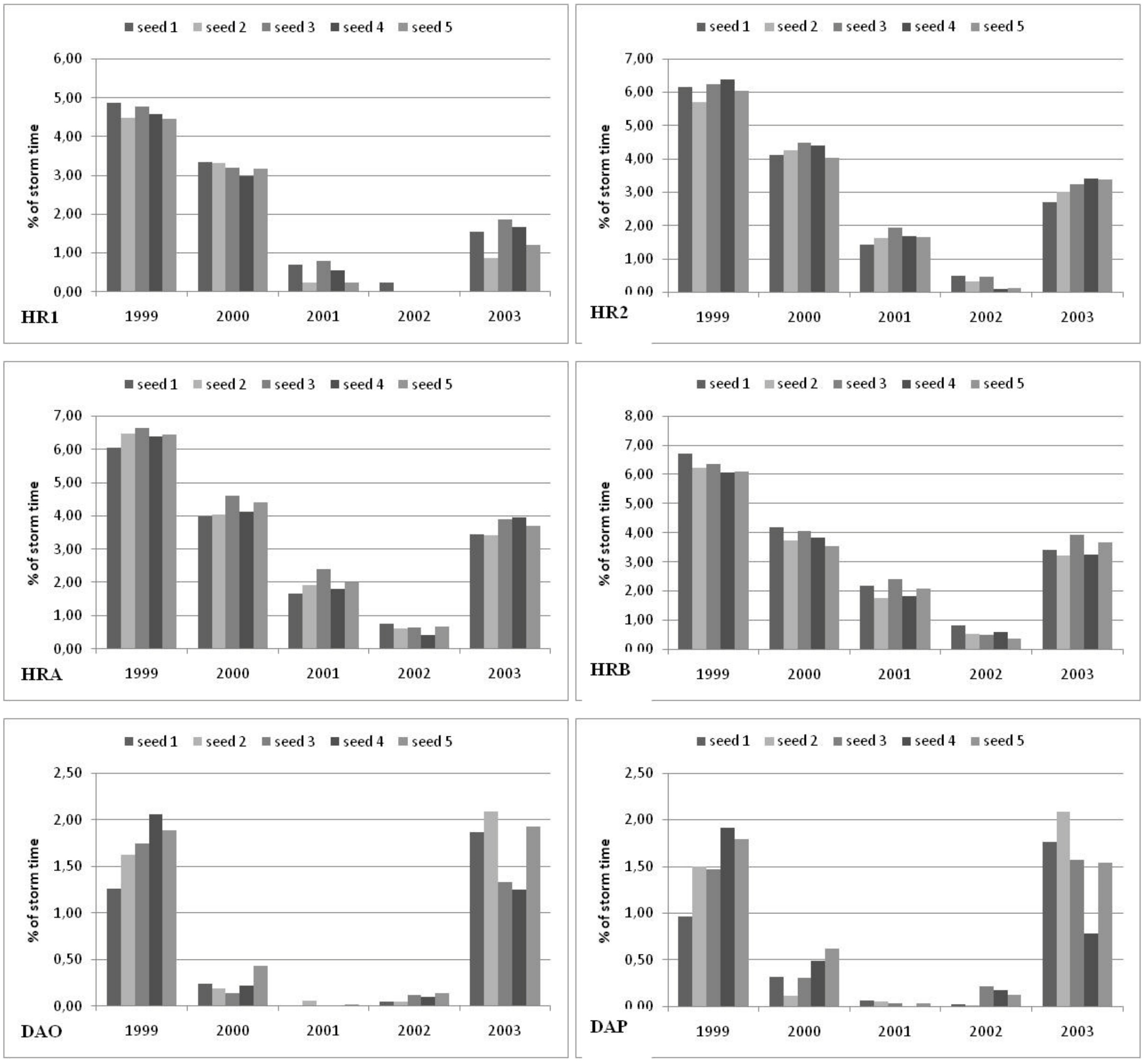


Figure 19 Loss of production as percentage of total storm time; SST control

The yearly statistics, presented in, indicate that both storm control strategy and geographical distribution of the wind farms have a strong influence on the total duration of loss of power. The total duration varies significantly from year to year, from as low as 15 hours to a little over 100 hours for Scenario 1, and from 2 to more than 62 hours for the second scenario.

Table 15 Loss of production; power system region year by year

			1999	2000	2001	2002	2003
hours	HST	Sc 1	110,78	93,98	43,27	14,61	40,92
		Sc 2	62,32	48,48	11,08	2,03	17,16
	SST	Sc 1	13,27	9,40	0,78	0,62	6,06
		Sc 2	5,12	1,32	0,00	0,00	0,99
% of	HST	Sc 1	10,99	9,59	4,25	1,50	4,34

storm time		Sc 2	12,64	10,11	2,44	0,47	3,05
	SST	Sc 1	1,32	0,96	0,08	0,06	0,64
		Sc 2	1,04	0,28	0,00	0,00	0,18

The average values, for the 25 annual time series simulated, given in Table 16, show that the storm control strategy has a major impact on the loss of production. For the first scenario, the total duration of the loss of production is decreasing with app. 90%, from 60 hours to 6 hours, which in percentage of the total storm time, means going from 6% to 0.6%. For the second scenario, the reduction is even bigger, going from 28 hours to 1.5 hours and from 5.7% to 0.3%.

Table 16 Loss of production; control strategy influence

Sc 1	Hours	HST	60,71
		SST	6,03
	% of storm time	HST	6,14
		SST	0,61
Sc 2	Hours	HST	28,21
		SST	1,49
	% of storm time	HST	5,74
		SST	0,30

When comparing the scenarios, the advantage of geographical distribution of the wind farms regarding the smoothening of the wind power over a power system region is clearly visible in Table 17. In addition to the control strategy used, simply by properly siting the wind farms one can achieve a reduction of more than 50% of the time when loss of production occurs.

Table 17 Loss of production; Scenario influence

		HST	SST
Hours	Sc1	60,71	6,03
	Sc2	28,21	1,49
	Diff	**32,50**	**4,54**
% of storm time	Sc1	6,14	0,61
	Sc2	5,74	0,30
	Diff	**0,39**	**0,31**

5.4. Ramp rates

The definition of ramp rates applied in this work is quite similar to the definition of load following applied by Parson et. al. [13]. The same definition of ramp rates was used in [14]. The intention is to quantify the changes in mean values from one period T_{per} to another, which specifies the ramp rate requirement that the wind farm power fluctuation causes to other power plants. Ramp rates are calculated only during SCEs.

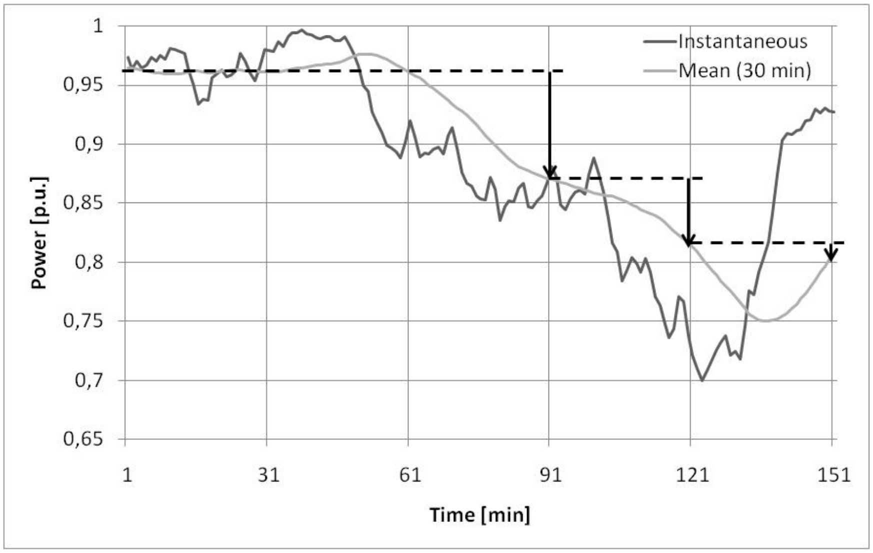


Figure 20 Definition of ramp rated for period time *T*per = 30 min. The ramp rates are indicated with arrows.

The definition of ramp rates is illustrated for period time T_{per} = 30 min in Figure 20. The instantaneous time series of power can be either measured or simulated. Then the mean value of the power is calculated at the end of each period, although it is illustrated for all time steps in Figure 20. The ramp rate is simply the change in mean value from one period to the next, i.e.

$$P_{\text{ramp}}(n) = P_{\text{mean}}(n+1) - P_{\text{mean}}(n) \tag{2}$$

Note that this definition specifies the ramping of the wind farm power. Thus, negative ramp rate means decreasing wind power, which requires positive ramping of other power plants.

The ramp rates were calculated for the two scenarios and for different time periods, from 5 to 45 minutes, in steps of 5 minutes and for both storm control strategies. The ramp rates for the short term variation, i.e. 5-15 minutes for both scenarios, are shown in Figure 21 and Figure 22, respectively.

The ramp rates for a longer period, i.e. 30 - 45 minutes, are presented in Figure 23 and Figure 24, respectively.

The SST control strategy clearly leads to smaller ramp rates than HST, as expected. On the other hand, the geographical dispersion of the wind farms has an impact on the ramp rates.

The 1% fractile, the one giving the extreme value of the decreasing wind power, for different time windows is presented in Figure 25.

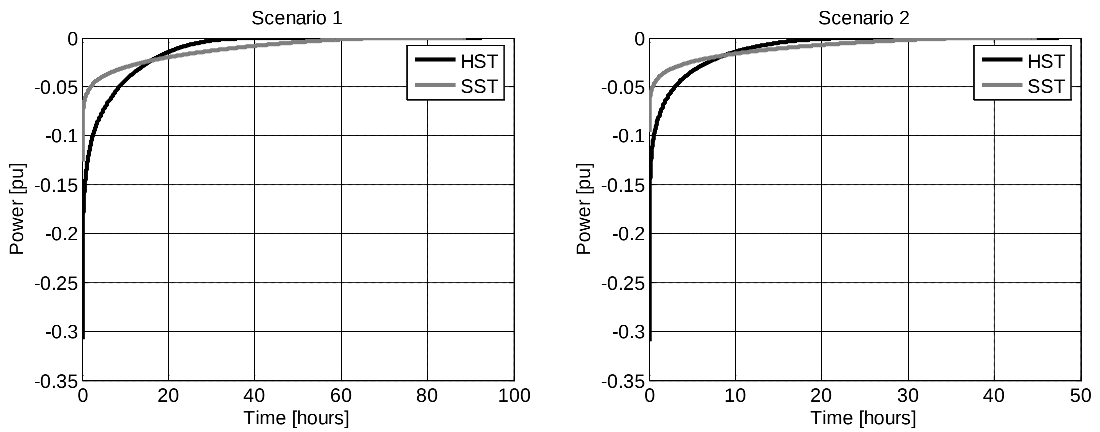


Figure 21 Five minutes period ramp rates

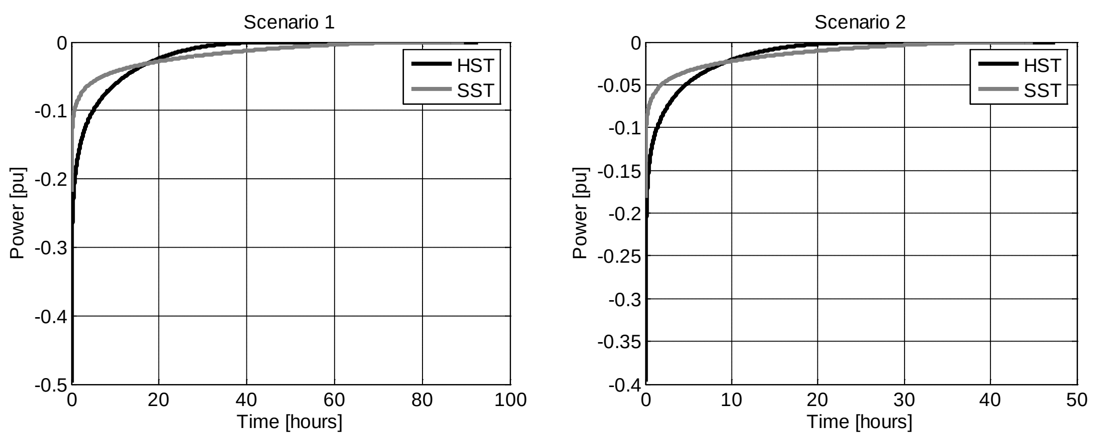


Figure 22 Fifteen minutes period ramp rates

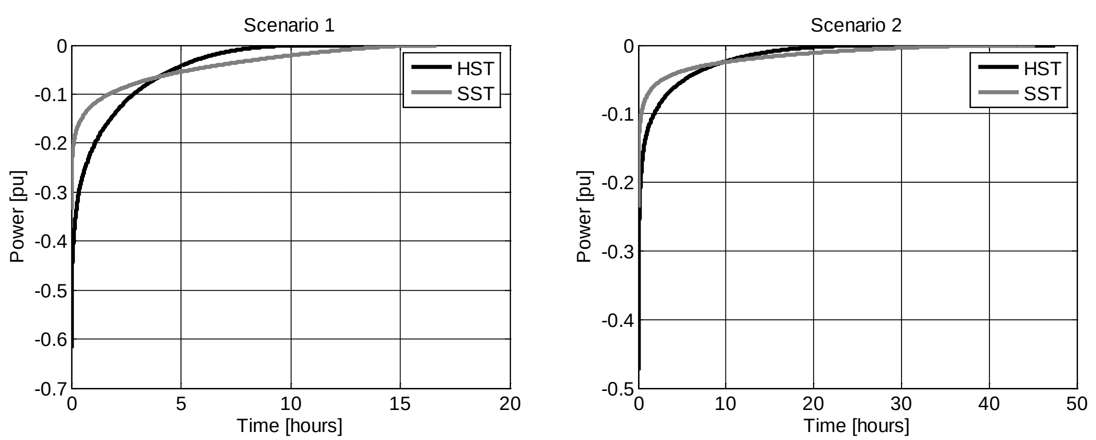


Figure 23 Thirty minutes period ramp rates

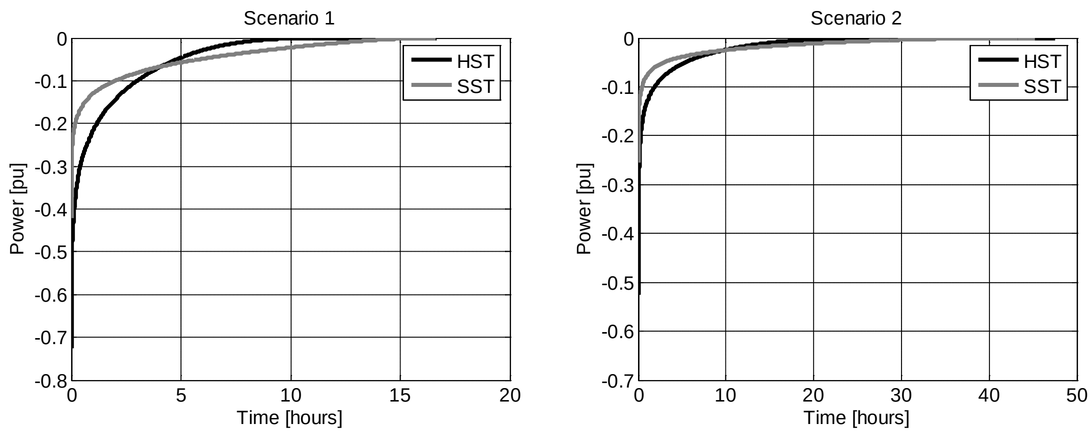


Figure 24 Forty-five minutes period ramp rates

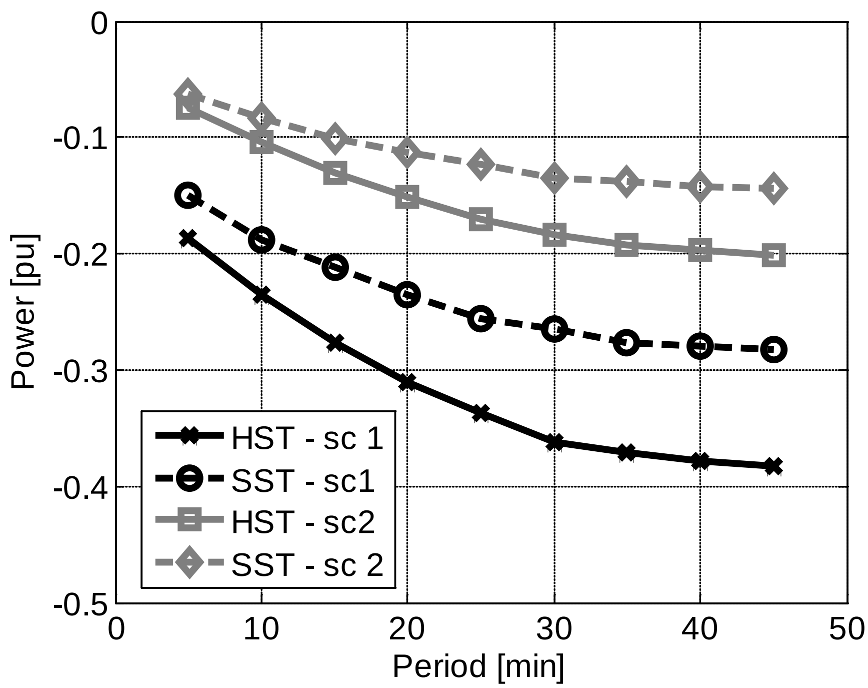


Figure 25 1% fractile versus time windows

For a clearer view of the differences between scenarios and control strategies, the numerical values of the 1% fractile are given in Table 18.

Table 18 1% fractile numerical values for different time horizons

Time horizon [min]		5	10	15	20	25	30	35	40	45
HST	Scenario 1	-0,19	-0,24	-0,28	-0,31	-0,34	-0,36	-0,37	-0,38	-0,38
	Scenario 2	-0,08	-0,10	-0,13	-0,15	-0,17	-0,18	-0,19	-0,20	-0,20
SST	Scenario 1	-0,15	-0,19	-0,21	-0,23	-0,26	-0,27	-0,28	-0,28	-0,28
	Scenario 2	-0,06	-0,08	-0,10	-0,11	-0,12	-0,13	-0,14	-0,14	-0,14

The ramp rates seem to depend more on the geographical location of the wind farms than on the storm control strategy used. The ramp rates for the second scenario are more than half compared to first scenario, while the control strategy manages to reduce the ramp rates by app. 30%, as shown in Table 18.

5.5. Reserve requirements

The definition of reserve requirements used in this work is similar to the one used in [13] and the same as the one used in [14]. The intention is to quantify the difference between the instantaneous power and the mean value which are dealt with as ramping. Reserves are calculated only during SCEs. Since the reserves must be allocated in advance, the positive reserve requirement is defined as the difference between the initial mean value and the minimum value in the next period.

This definition of reserve requirements is illustrated for period time T_{per} = 30 s in Figure 26. Formally, the reserve requirements are defined as

$$P_{\mathrm{ramp}}(n) = P_{\mathrm{mean}}(n) - P_{\mathrm{min}}(n+1) \tag{3}$$

Note that with this definition, positive reserves means decreasing wind power that requires positive reserves form other power plants.

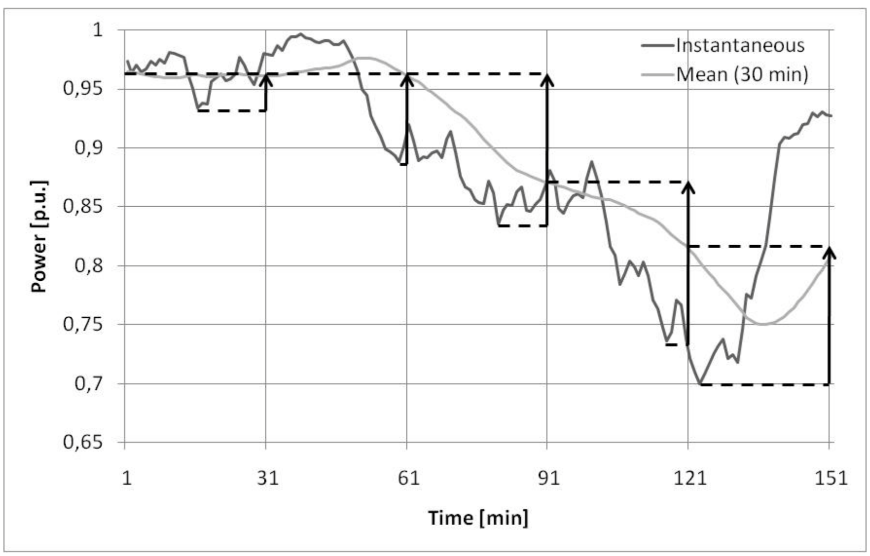


Figure 26 Definition of reserves for period time *T*per = 30 min. The reserves are indicated with arrows.

The reserves were calculated for the two scenarios and for different time periods, from 5 to 45 minutes, in steps of 5 minutes and for both storm control strategies. The ramp rates for the short term variation, i.e. 5-15 minutes for both scenarios, are shown in Figure 27 and Figure 28, respectively. The ramp rates for a longer period, i.e. 30 - 45 minutes, are presented in Figure 29 and Figure 30, respectively. The 1% fractile, the value on the extreme of the duration curve, is shown in Figure 31 versus the time windows.

Similar to the ramp rates, the reserves seem to be more sensitive to the geographical dispersion of the wind farms than on the storm control strategy.

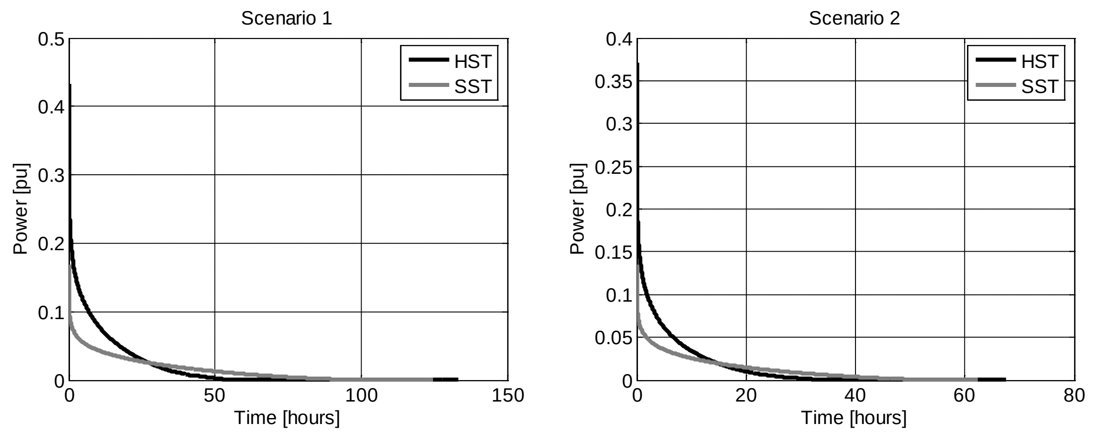


Figure 27 Five minutes period reserves

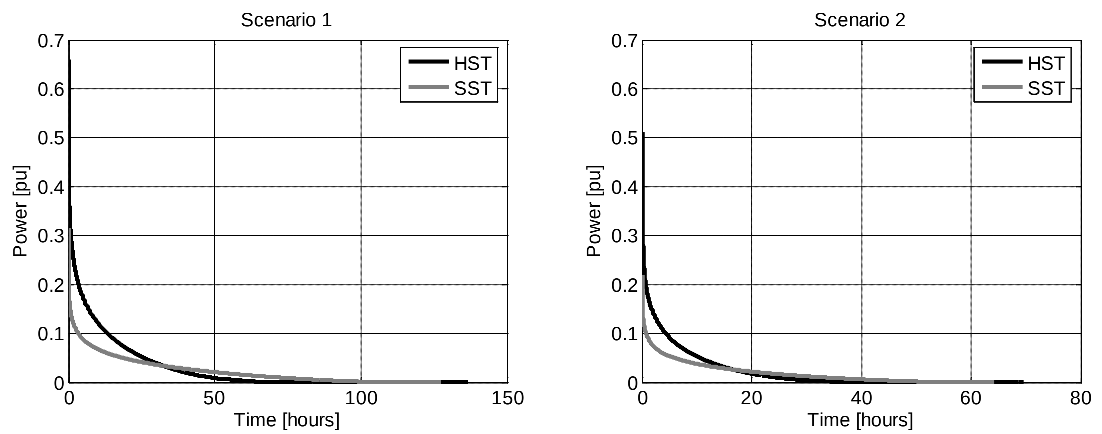


Figure 28 Fifteen minutes period reserves

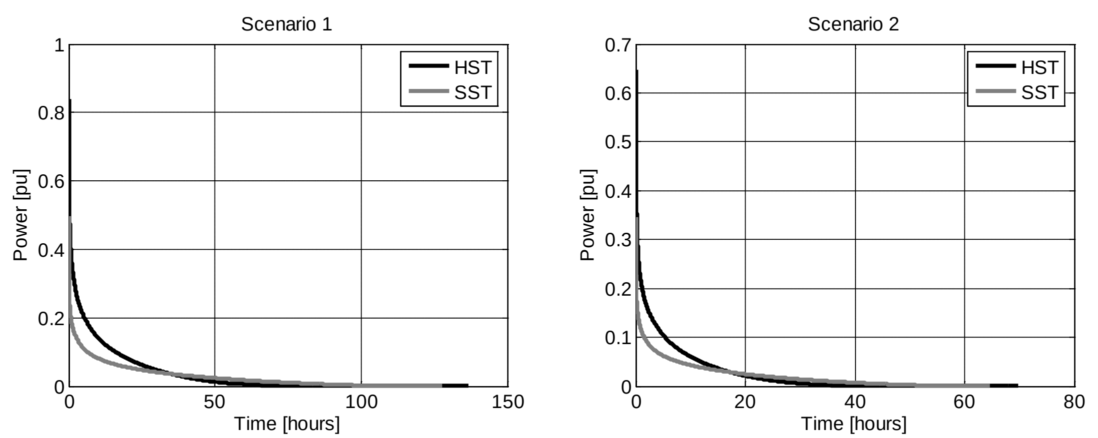


Figure 29 Thirty minutes period reserves

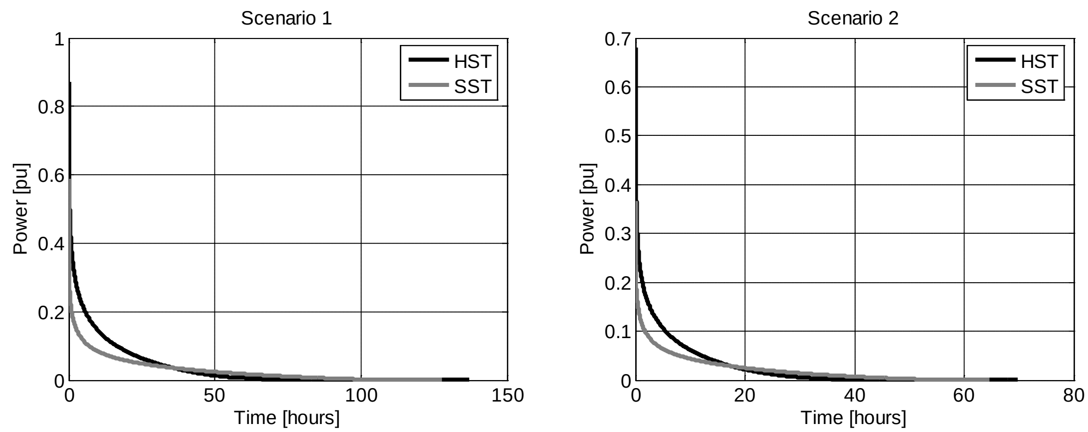


Figure 30 Forty-five minutes period reserves

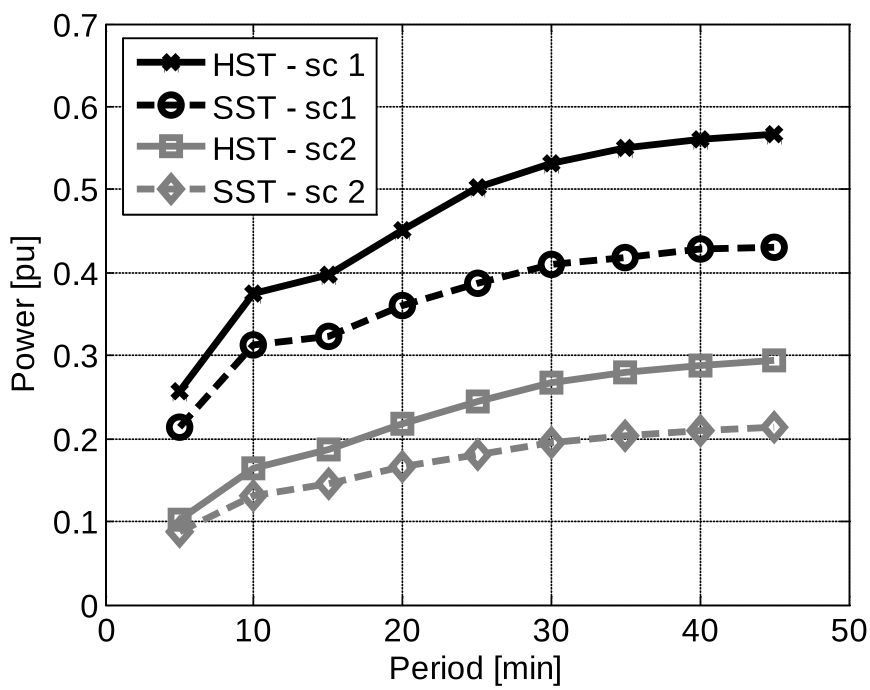


Figure 31 Reserves versus time windows

Table 19 1% fractile of reserves numerical values for different time horizons

Time horizon [min]		5	10	15	20	25	30	35	40	45
HST	Scenario 1	0,26	0,34	0,40	0,45	0,50	0,53	0,55	0,56	0,57
	Scenario 2	0,10	0,15	0,19	0,22	0,25	0,27	0,28	0,29	0,29
SST	Scenario 1	0,21	0,27	0,32	0,36	0,39	0,41	0,42	0,43	0,43
	Scenario 2	0,09	0,12	0,15	0,17	0,18	0,19	0,20	0,21	0,21

The reduction of the reserves achieved by the proper siting of a wind farm is bigger than the one provided by the storm control, as the values of the 1% fractile (Table 19) show. The reduction achieved by the distributed scenario is more than half for all time windows considered, while the storm control reduces with maximum 30% the reserves requirements. Of course, a combination of both proper siting and adequate control strategy will lead to very significant reductions of the reserves requirements, in the range of 60-70%.

6. Discussion

As mentioned earlier, the REMO data are given at a height of 10 m. Therefore, the values need to be scaled to the hub height of modern wind turbines. In the present version of CorWind, a simple scaling by a constant is applied, and this constant is calibrated so that the specified annual mean wind speed at the specific wind turbine is obtained. This is a very simple approach, which can be questioned, especially when the focus is on the storm wind speeds with relatively low probability. This can be seen in Figure 32, where the distribution of simulated with the same five seeds used above and measured ones are plotted. The data are 10-min averages from a met mast installed at Horns Rev 1. The simulation was done for the same met mast and for the same height at which the anemometer in installed on the met mast. The results indicate that the constant factor scaling leads to under simulate lower wind speeds, i.e. 5 – 10 m/s and over simulate extreme wind speeds, i.e. over 20 m/s.

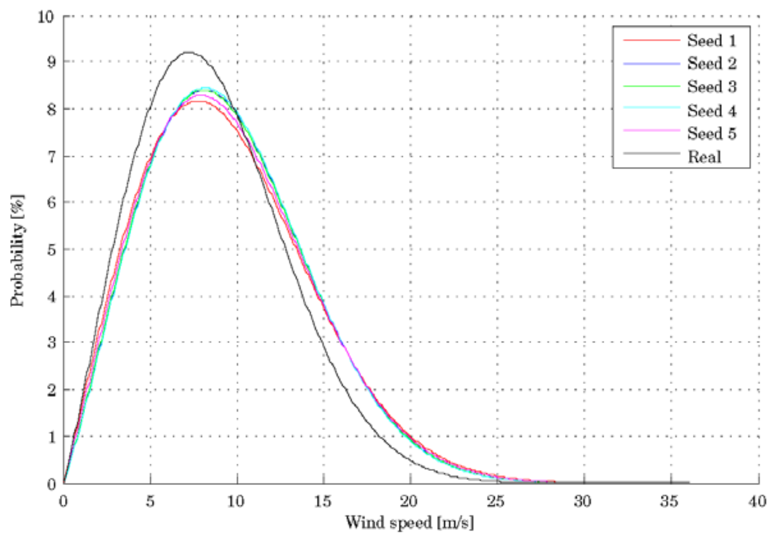


Figure 32 Comparison between simulations and real data with Weibull fitting

7. Conclusions

This report deals with the reliability of offshore wind production under extreme wind conditions.

Simulations results of the wind power variability from existing and future large offshore wind farms in Western Denmark were used to investigate the influence of the control strategy and of the spatial distribution on the operational reliability of large offshore wind farms.

The analysis involved several aspects inspired from reliability studies. The aspects investigated are storm events occurrences and durations, storm control strategy impact on the capacity factor (lost production), the loss of production (power produced from wind drops below a certain threshold due to high wind speeds and storm controller) and finally, the wind power production ramp rates and reserves requirements.

Control strategies play a crucial role in increasing the reliability of offshore wind farms power production under extreme wind conditions.

Availability of wind power production at power region level can be improved by proper wind farm location selection.

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